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Research Article

The Reaction Cross Sections for ^{124,125}Te(p,xn)^{123,124}I and ^{123,124}Te(d,xn)^{123,124}I

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Abstract

The iodine isotopes of ^{123}I and ^{124}I with half lives of 13.2 hours and of 4.2 days respectively are commonly used in nuclear medicine and are becoming more widespread recently. The isotope of ^{123}I is ideal for a gamma camera with the energy of 159 keV to the patient with a much less radiation dose whereas the radionuclide ^{124}I is a positron emitter and is useful in some positron emission tomography (PET) for radiopharmaceuticals. The gamma ray will penetrate tissue very effectively without an excessive radiation dose. Iodine-123 decays by electron capture emitting gamma rays at 0.028 and 0.160 MeV that has high penetration power to tissue but no excessive radiation dose. The half-life of 4.2 d and the 23% positron decay allow localization with monoclonal antibodies, and the PET imaging which makes Iodine-124 radionuclide a good candidate for being a diagnostic and a therapeutic.This study aims on the calculation of the excitation functions for ^{123}I and ^{124}I various production mechanisms. TALYS 1.6 is used to calculate the reaction cross sections for ^{123,124,125}Te bombarded with protons and deuteriums to produce ^{123,124}I radioisotopes commonly used in medical applications. The calculated results were compared with available experimental results from EXFOR. The results are interpreted in terms of deciding which radioisotope is more appropriate to produce with which reaction and evaluating the effects in the reaction mechanisms. In addition, the relative reaction cross-sections of ^{123,124}I radioisotopes obtained by bombarding ^{124}Te target with protons were discussed, and the common reaction for the production of ^{123}I was evaluated to be the ^{124}Te(p, 2n)^{123}I reaction on the highly enriched ^{124}Te. Thus, it is considered that a very high level of enrichment on the target must be achieved in order to prevent contamination caused by competing reactions of (p, n) and (p,2n). It is concluded that ^{123}I production is more suitable for small and mediumi-sized cyclotrons.

Keywords: Excitation Functions, Charged Particle Induced Reactions, Iodine Production Cross Sections, TALYS 1.6, EXFOR.

^{124,125}Te(p,xn)^{123,124}I ve ^{123,124}Te(d,xn)^{123,124}I İçin Reaksiyon Tesir Kesitleri

Öz

İyodin izotopları, 13.2 saat yarı ömürlü ^{123}I ve 4.2 gün yarı ömürlü ^{124}I, son zamanlarda genelde nükleer tıp alanında yaygın olarak kullanılırlar. ^{123}I izotopu hastaya çok daha düşük bir radyasyon dozu verir ve 159 keV gama ışını enerjisine sahip bir gama kamerası için idealdir, oysa radyonüklid ^{124}I bir positron yayıcıdır ve radyofarmasötikler için bazı pozitron emisyon tomografisinde (PET) yararlıdır. Gama ışını, aşırı radyasyon dozu olmadan dokuya çok etkili bir şekilde nüfuz eder. ^{123}I, elektron yakalama ile 0.028 ve 0.160 MeV'de iki ana gama ışını ile %100 bozunur. 4.2 d'nin yarı ömrü, monoklonal antikorlarla lokalizasyon için yeterince uzundur ve %23 pozitron bozunması, PET ile görüntülemeye izin verir. ^{124}I, hem diagnostik hem de terapötik bir radyonüklid olarak potansiyele sahiptir. Bu çalışmada, ^{123}I ve ^{124}I için önerilen çeşitli üretim mekanizmaları için uyarma fonksiyonları hesaplanmıştır. ^{123,124,125}Te hedef çekirdeklerinin protonlar ve döteryumlarla indüklenmesi sonucu tıbbi uygulamalarda yaygın olarak kullanılan ^{123,124}I radyoizotoplarının

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üretilmesini sağlayan nükleer reaksiyonları için reaksiyon tesir kesitleri TALYS 1.6 kullanılarak hesaplandı. Hesaplamalardan elde edilen sonuçlar EXFOR deneysel veri tabanında mevcut olan deneysel sonuçlarla karşılaştırılmıştır. Sonuçlar hangi radoizotopun hangi reaksiyon ile üretilmesinin daha uygun olacığına karar vermek ve reaksiyon mekanizmalarında yer alan etkilerin değerlendirilmesi açısından yorumlanmıştır. Ayrıca, ^{124}Te hedefinin protonlarla indüklenmesiyle elde edilen ^{123,124}I radyoizotoplarının göreceli reaksiyon tesir kesitleri tartışılmış ^{123}I üretimi için ortak reaksiyonun oldukça zenginleştirilmiş ^{124}Te üzerindeki ^{124}Te (p, 2n) ^{123}I reaksiyonu olduğu değerlendirilmiştir. Böylece bir reaksiyon esnasında (p, n) ve (p, 2n) gibi birbiriyle yarışması muhtemel reaksiyon mekanizmalarının oluşturduğu kontaminasyonun önüne geçilmesi için hedef üzerinde oldukça yüksek düzeyde zengişlendirme işleminin öncelikli olarak yapılmasının bir gereklilik olduğu düşünülmektedir. ^{123}I üretiminin küçük ve orta boy siklotronlar için daha uygun olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Uyarılma Fonksiyonları, Yüklü Parçacık İndüklü Reaksiyon, İyot Üretim tesir Kesitleri, TALYS 1.6, EXFOR.

1. Introduction

Radioisotopes are generally produced in cyclotrons or reactors to be used forpurposes of treatment or diagnosis in the healthcare field. The reaction is produced by the radioisotopes, the energy of the projectile particles to be used in production, the target core and the cross-sections of the reaction are determined. For cases where carriying out an experiment is difficult and expensive, it is widely preferred to perform simulation studies which save both time and economy (Gürol et al., 2020).

The Iodine-123 is a gamma emitter with a half live of 13.2 hours is used for diagnosis of thyroid function. Because of its patient-friendly properties, ^{123}I is being used widely in nuclear medicine. The use of ^{124}I radioisotope has extended in medicine recently due to its diagnostic and therapeutic potential. Since its half life is 4.2 days and it has 23% positron decay (IAEA, 2009); it is possible to use ^{124}I for positron emission tomography (PET) radiopharmaceuticals (Glaser et al., 2001; Sheh et al., 2000; Michael et al., 1981). ^{124}I isotope were formerly considered as an impurity in ^{123}I production, since it has diagnostic and therapeutic potential the production of ^{124}I is becoming more widespread (Herzog et al., 2002; Pentlow et al., 1996).

^{123}I have been produced through several reactions and methods in the past (Watson et al., 1973; Kondo et al., 1977; Beyer et al., 1981; Michael et al., 1981; Clem and Lambrecht, 1991; Firouzbakht et al., 1993; Hohn et al., 2001). However, some of them require high energy cyclotrons or reactor processes. Due to the localization and economical requirements ^{124}Te(p,2n)^{123}I and ^{124}Te(d,3n)^{123}I reactions were found more suitable for ^{123}I production and has been widely used (IAEA, 2009). ^{124}Te(p,2n)^{123}I and ^{124}Te(d,3n)^{123}I reactions require highly enriched ^{124}Te in order to minimize the possible contamination in the target material (Braghirolli et al., 2014; Herzog et al., 2002; Sheh et al., 2000; Goriely, 1998; Kondo et al., 1977). ^{124}Te(p,2n)^{123}I and ^{124}Te(d,3n)^{123}I reactions are suitable for small and medium sized cyclotrons respectfully. The ^{124}Te(d,2n)^{124}I reaction were used to produce ^{124}I from enriched ^{124}Te. Recently ^{124}Te (p, n)^{124}I reaction is used to produce ^{124}I. The ^{124,125}Te (p, xn)^{124}I and ^{123,124}Te (d,xn)^{124}I reaction cross sections are essential to determine the best possible way to produce ^{124}I, since different production methods will result in different impurities and economical viabilities viabilities (Braghirolli et al., 2014; Sadeghi et al., 2010; Sadeghi et al., 2008; Bastian et al., 2001; Clem and Lambrecht, 1991; Firouzbakht et al., 1993).

Therefore, TALYS 1.6(Koning et al., 2007) was used to calculate the charged particle induced reactions of ^{123,124}Te(p,2n)^{123}I and ^{124}Te(d,3n)^{123}I leading to ^{123}I cross sections and ^{123,124}Te(p,xn)^{124}I and ^{123,124}Te(d,xn)^{124}I leading to ^{124}I cross sections. The calculated reaction cross sections were compared with reported experimental results. Moreover, the production rates are compared with a comment on contamination concerns.

2. Material and Method

TALYS 1.6 computer code (Koning et al., 2007) includes nuclear reactions with default physical models as well as specific options that can be assigned by user to address the physics of the reaction (Gamma strength functions, Pre-equilibrium Models, Pre-equilibrium spin distributions, Optical model parameters, Fission parameters, Level density parameters, Exciton models, Continuum stripping, pick-up, break-up and knock-out reactions). The computer code includes photon, neutron, proton, deuteron, triton, ^{3}He, and α-particles as both projectiles and ejectiles. All experimental information on nuclear masses, deformation, and low-lying states spectra is considered, various local and global input models have been incorporated to represent the nuclear structure properties, optical potentials, level densities and γ-ray strengths. The pre-equilibrium particle emission is described by using the two-component Exciton model. For the pre-equilibrium complex particle emission, the phenomenological model is used. Hauser-Feshbach formalism is used to describe the equilibrium particle emission (Sadeghi et al., 2010).

^{124}Te(d,3n)^{123}I reaction cross section were calculated using; Brink-Axel lorentzian for gamma strength functions, generalized superfluid model (GSM) for level densities, Numerical transition rates for preequilibrium model (Koning et al., 2007). Moreover, the most compatible results were compared with the experimental data available in literature (EXFOR).

3. Results and Discussion

TALYS 1.6 was used to calculate the reaction cross sections of ^{124}Te(p,2n)^{123}I and ^{124}Te(d,3n)^{123}I leading to ^{123}I and ^{124}Te(p,n)^{124}I, ^{125}Te(p,2n)^{124}I, ^{123}Te(d,n)^{124}I and ^{124}Te(d,2n)^{124}I leading to ^{124}I. The calculated results were compared with the available experimental data from EXFOR. The reaction cross section results of producing ^{123}I are given in Figs. 1 and 2, and the similar results for the production of ^{124}I are shown in Figs. 3-6. Moreover, the relative reaction cross section results of the production of both isotopes from different reactons on ^{124}Te is compared in Fig. 7.

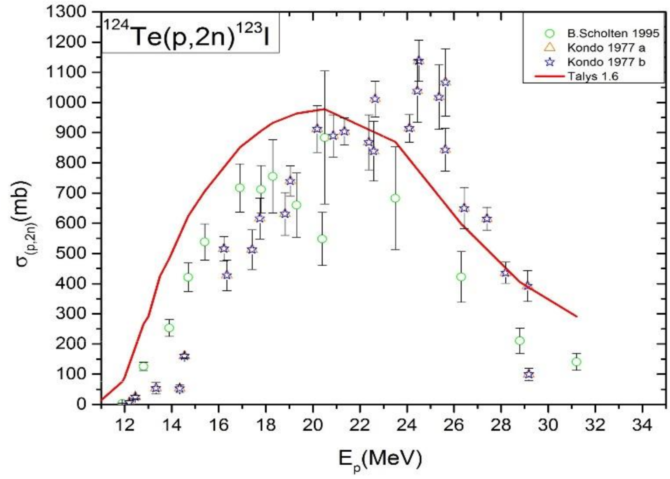

Fig 1. Reaction cross sections of producing ^{123}I from $^{124}Te(p,2n)^{123}I$.

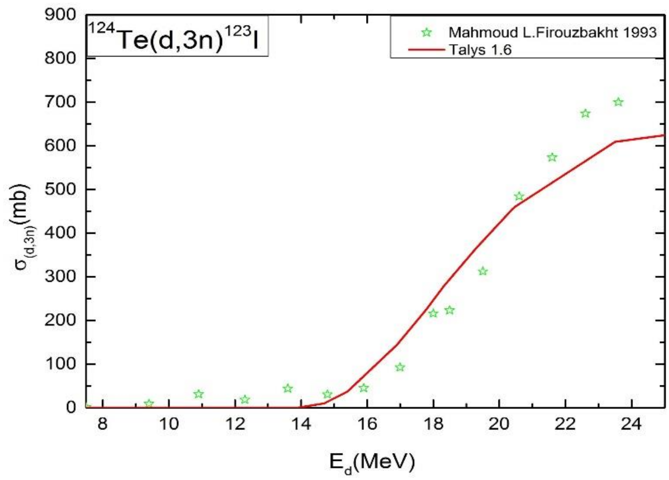

Fig 2. Reaction cross sections of producing ^{123}I from $^{124}Te(d,3n)^{123}I$.

$^{124}Te(p,2n)^{123}I$ and $^{124}Te(d,3n)^{123}I$ reaction cross sections were calculated using Goriely's hybrid model (Goriely, 1998) for gamma strength functions, microscopic level densities (temperature dependent HFB, Gogny force) from Hilaire's combinatorial tables for level density model. Exciton model were selected as analytical transition rates with energy-dependent matrix element for pre-equilibrium, since the medical isotope production were implemented just recently to TALYS 1.6 and is only using analytical formalism (Koning et al., 2007). The calculated $^{124}Te(p,2n)^{123}I$ reaction cross sections were compared with the experimental data measured by Scholten et al., (1995) and Kondo et.al., (1977). Present calculation is fairly in good agreement with both experimental data by remaining in between them, showing good approximation around the peak with a promising cross section value over 900 mb. However, there are some discrepancies in low and high energy regions (10-18 MeV, 25-30 MeV). It is clear that the $^{124}Te(p,2n)^{124}I$ reaction is promising and compatible for small, medium cyclotrons for ^{123}I production (see Fig.1). The calculated $^{124}Te(d,3n)^{123}I$ reaction cross sections were compared with the experimental data measured by Firouzbakht et al., (1993). Present calculation is in good agreement with experimental data, remaining in between the two experimental data, showing good curve approaching the peak with a promising cross section value over 600 mb. It is clear that the $^{124}Te(d,3n)^{123}I$ reaction is promising and compatible for medium cyclotrons for ^{123}I production (see Fig.2).

The excitation functions were calculated for various production mechanisms. ^{124}I cross sections were calculated for $^{124}Te(p,n)^{124}I$, $^{125}Te(p,2n)^{124}I$, $^{123}Te(d,n)^{124}I$ and $^{124}Te(d,2n)^{124}I$ by using TALYS 1.6. The calculated results and available measurements in literature were given in Figs. 3-6, respectively.

The calculated $^{124}Te(p,n)^{124}I$ reaction cross sections were compared with the experimental data measured by Scholten et al., (1995). The present calculation is in good agreement with the experimental data.

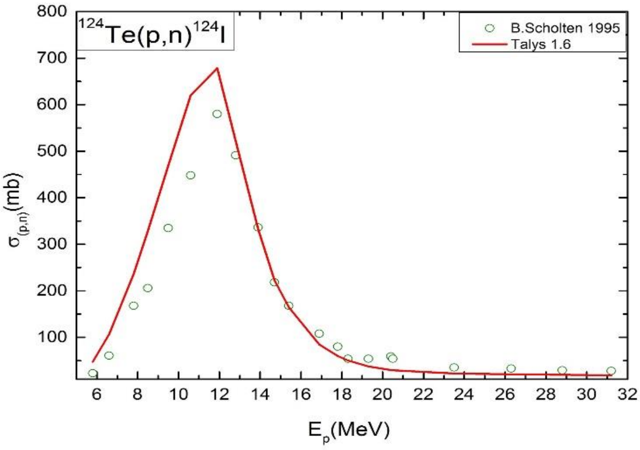

Fig 3. Reaction cross sections of producing ^{124}I from $^{124}Te(p,n)^{124}I$.

The calculated ^{125}Te(p,2n)^{124}I reaction cross sections were compared with the experimental data measured by Hohn et al., (2001). The present calculation is in an excellent agreement with the experimental data.

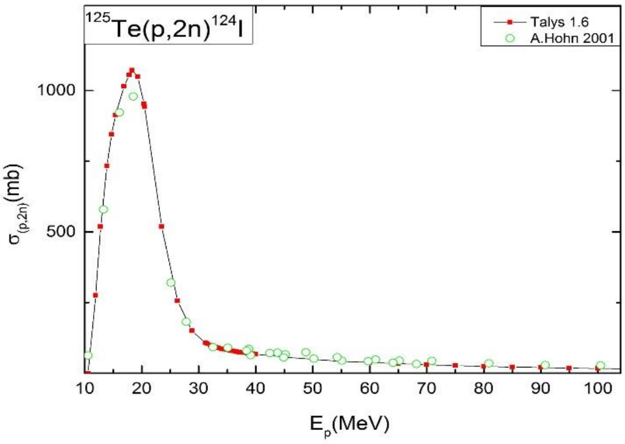

Fig 4. Reaction cross sections of producing ^{124}I from $^{125}Te(p,2n)^{124}I$.

The calculated ^{123}Te(d,n)^{124}I reaction cross sections were compared with the experimental data measured by Scholten et al., (1995). The present calculation is fairly in agreement with the experimental data.

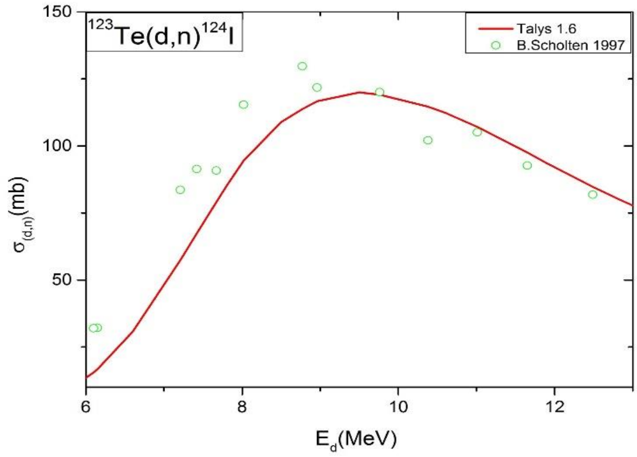

Fig 5. Reaction cross sections of producing ^{124}I from $^{123}Te(d,n)^{124}I$.

The calculated ^{124}Te(d,2n)^{124}I reaction cross sections were compared with the experimental data (Firouzbakht et al., 1993; Bastian et al., 2001). The present calculation is in good agreement with Bastian et al., (2001) and the cross-section values reported by the IAEA (IAEA, 2009). The calculated cross sections for ^{124}Te(d,2n)^{124}I reaction deviates from the experimental data measured by Firouzbakht et al. (1993) by a big margin. However, if the cross-section values measured by Firouzbakht et al. (1993) is multiplied by 10, the cross section-energy plot becomes in good agreement with the plot given by the IAEA (200).

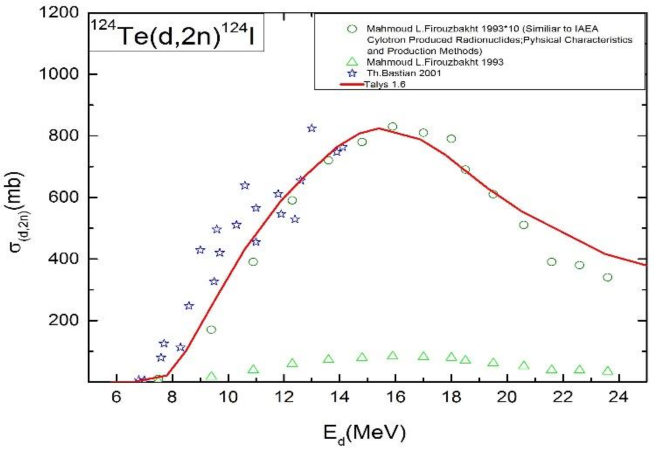

Fig 6. Reaction cross sections of producing ^{124}I from ^{124}Te(d,2n)^{124}I.

The calculated ^{124}Te(p,2n)^{123}I reaction cross sections were compared with both the calculated ^{124}Te(p,n)^{124}I reaction cross sections and the experimental data measured by Scholten et al., (1995) and Kondo et al., (1977), respectively. A minimum contamination can be seen starting around 10 MeV, peaking around 13 MeV and decreases with increasing energy. So, it is clear that the elimination of radionuclidic impurities is not always possible even with a wide energy selection and high enrichment as stated by Glaser et al., (2001), Sheh et al., (2000) and Michael et al., (1981). The production of ^{123}I were found appropriate for small, medium-sized cyclotrons and is convenient for economical and availability purposes.

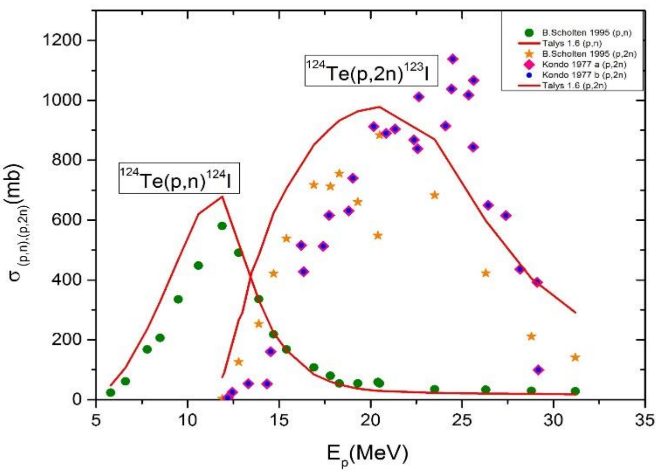

Fig 7. Comparison of reaction cross sections of producing ^{123,124}I from ^{124}Te(p,n)^{124}I and ^{124}Te(p,2n)^{123}I.

4. Conclusions and Recommendations

The ^{124}Te (p,n)^{124}I reaction is very promising and compatible for small cyclotrons. The production of ^{124}I trough ^{125}Te(p,2n)^{124}I reaction is suitable for medium size cyclotron since the peak of the graphic is around 20 MeV with a cross section value over 10^3 mb around 18-22 MeV region (see Fig.4). Tough there are small discrepancies on low energies, between 8-12 MeV region, the calculated results show the ^{124}I production trough ^{123}Te(d,n)^{124}I reaction is suitable for low energy cyclotron (see Fig.5). For ^{124}Te(d,2n)^{124}I reaction both TALYS code calculation results and the experimental data gives peak around 15 MeV with reaction cross section values over $8x10^2$ mb. ^{124}Te(d,2n)^{124}I reaction is suitable for small energy cyclotron (see Fig.6).

After a careful literature search for ^{124}Te(d,2n)^{124}I reaction it was found that the experimental data that measured by Firouzbakht et al. (1993) was reported erroneously in the IAEA (2009). The discrepancy between Firouzbakht et al. (1993) and IAEA (2009) needs to be resolved. We do not know how to consolidate this difference. To point out an interesting fact that, if one multiplies the cross-section values in Firouzbakht et al. (1993) by 10 one would acquire similar values to our present calculation and also as reported in the IAEA (2009).

After comparisons most promising reactions leading to ^{124}I production seems to be ^{124}Te (p, n)^{124}I, and ^{125}Te(p,2n)^{124}I reactions. However, ^{125}Te(p,2n)^{124}I reaction has disadvantages such as high incident proton energy requirements and impurity of yield nuclei. Additionally, ^{123}Te (d, n)^{124}I reaction has a big disadvantage on material cost and with a low cross section value around 8-12 MeV peak little over 100 mb.

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